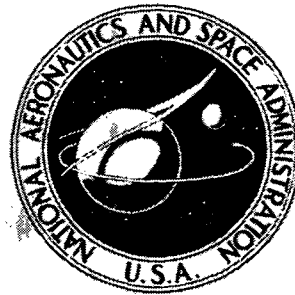


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**THE DOPEX CODE - AN APPLICATION
OF THE METHOD OF STEEPEST DESCENT TO
LAMINATED-SHIELD-WEIGHT OPTIMIZATION
WITH SEVERAL CONSTRAINTS**

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THE DOPEX CODE - AN APPLICATION OF THE METHOD OF STEEPEST DESCENT TO LAMINATED-SHIELD-WEIGHT OPTIMIZATION WITH SEVERAL CONSTRAINTS

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SUMMARY

A two- or three-constraint, two-dimensional radiation shield weight optimization procedure and a computer program, DOPEX, is described. The DOPEX code uses the steepest descent method to alter a set of initial (input) thicknesses for a shield configuration to achieve a minimum weight while simultaneously satisfying dose constraints. The code assumes an exponential dose-shield thickness relation with parameters specified by the code user. The code also assumes that dose rates in each principal direction are dependent only on shielding thicknesses in that direction. The code will presently handle problems with one constraint (spherical geometry), or two or three constraints (right circular cylindrical geometry). Other geometries may be used if one subroutine is changed to suit the application. Code input instructions, a FORTRAN IV listing, and a sample problem are given. Typical computer time required to optimize a seven-layer shield is less than 0.1 minute on an IBM 7094-II.

INTRODUCTION

One-dimensional shield weight optimization procedures have been established for radiation shield design (refs. 1 and 2). Optimization procedures such as these take some initial configuration specified by the user and alter the thickness of each layer to achieve a minimum weight while simultaneously satisfying a dose constraint. One method used to seek the minimum weight configuration from a starting configuration is that of steepest descent.

Bernick (ref. 3) developed an algorithm to optimize one-dimensional shields utilizing the steepest descent method which was programmed as the OPEX code (ref. 4).

OPEX was later reprogrammed as the OPEX II code (ref. 5). This report presents the DOPEX code, an extension of this type of procedure to two dimensions with two or three constraints. The statement of the optimization algorithm and the derivation of the expression for the steepest descent vector were made in reference 6 for the general multi-dimensional, multiconstraint case. The present procedure considers only the special case where doses in each principal direction are dependent only upon the shielding thickness in that direction. This particular dose-thickness model is valid for many configurations of interest.

The geometry and thicknesses of material determine the weight and the derivative of weight with respect to thickness. With first derivatives of both weight and dose with respect to thickness, the optimization procedure alters the base configuration to obtain a set of thicknesses corresponding to a minimum weight configuration while meeting the dose constraints. This code does not select materials but merely alters initial configurations. DOPEX may eliminate layers but it never adds layers. The accuracy of the optimization procedure depends on the ability of the dose-thickness relation to accurately represent the actual dose and changes of dose with thickness in the real geometry. Although the present model has been reasonably successful, a final detailed proof calculation is necessary to confirm dose predictions of the optimization code for the resultant optimized geometry. It is realized that some shield shaping (e.g., rounding of the corners) may result in further weight reduction over that predicted by an optimization. But such a procedure is beyond the scope of this report.

The two-dimensional shield-weight optimization code DOPEX¹ described here is designed for one, two, or three constraints. The subroutine WEIGHT included in this report is presently programmed for one-constraint spherical geometry (same as in ref. 5) and two- and three-constraint right circular cylinders. Any different geometry that is being considered requires writing a new subroutine WEIGHT for that geometry. In this report, a description of how to obtain the necessary input data for DOPEX is given. Data input instructions, a FORTRAN IV code listing, and a sample problem optimizing a three-constraint seven-layer shield of tungsten and lithium hydride for a space power reactor are given.

DOSE-THICKNESS RELATION

The total radiation dose rate D_m at some reference point in space is defined, for purposes of the optimization procedure, to be:

¹In the evolution of this code from the original OPEX code, one version was called D'OPEX standing for double-constraint OPEX. Although the code was extended to three constraints, the name DOPEX was retained.

$$D_m = \sum_i^{IMAX_m} D_{im} \quad (1)$$

where

D_{im} i^{th} component of m^{th} total dose rate (e.g., dose due to capture gammas from first shield layer or dose due to inelastic gammas from last shield layer, etc.)

D_m total dose rate in m^{th} direction (i.e., at m^{th} constraint point)

$IMAX_m$ number of components of dose in m^{th} direction

Each dose component D_{im} is further assumed to be of the form

$$D_{im} = C_{im} \exp \left(- \sum_{j=1}^{NREG_m} \mu_{ijm} t_{jm} \right) \quad (2)$$

where

C_{im} fitted parameter

$NREG_m$ number of regions present in m^{th} direction

t_{jm} thickness of j^{th} region in m^{th} direction

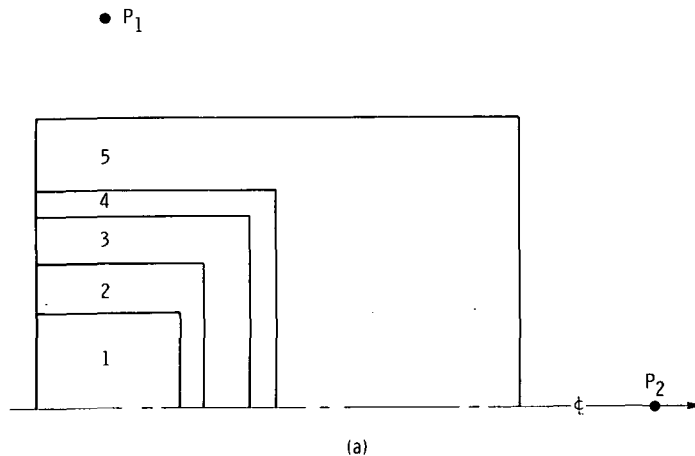
μ_{ijm} "attenuation coefficient" which describes effect of change in thickness t_{jm} on D_{im}

Subdividing the total dose rate into its components and evaluating coefficients μ_{ijm} separately for each component dose rate results in a total dose model having a set of coefficients which is relatively insensitive to changes in thicknesses of layers. (See, e.g., the approach used in ref. 1.) Other forms of the dose-thickness relation could be utilized but this would require reprogramming the subroutine which calculates dose and dose gradients. The parameters in this empirical expression are assumed to be obtained by fitting to accurate, detailed radiation transport calculations of dose rate for a given base configuration and perturbations of that configuration.

Notice from equation (2) that the m^{th} dose is alterable only by thicknesses in that direction. This assumption was made in the final derivation of the equations in reference 6 because it may be virtually impossible to write a dose equation such as equation (2) involving n-dimensional shields. The user is cautioned to be aware of the classical shielding booby traps of very asymmetric shields which may be generated by this code (or any other such code) which uses a "line-of-sight" type of representation of the

dose-thickness model. Although the doses in the various directions are decoupled from one another, the derivatives of weight, dose, and products of these are not. Note that there may be more than one contribution to the total dose from a given layer. Other layers may contribute negligible secondary gamma dose and their dose contribution is omitted. Generally because of differences in formation rate and gamma attenuation, a given high-Z shield region will have one dose component due to capture gammas and a second due to inelastic gammas. The core will have primary neutrons and primary gammas. A hydrogenous layer may have negligible dose.

For example, consider the cylindrical reactor-shield described in sketch (a) and the following table with a dose constraint at points P_1 and P_2 :



Region j (both di- rections)	Description	Radiation dose com- ponent i	Description
1	Reactor core	1	Core neutron
		2	Core gamma
2	Reflector	3	Capture gamma
		4	Inelastic gamma
3	Lithium hydride	---	Negligible dose
4	Tungsten shield	5	Capture gamma
		6	Inelastic gamma
5	Lithium hydride	---	Negligible dose

In this example, $\mu_{2,4}$, $\mu_{3,4}$, and $\mu_{4,4}$ for directions 1 and 2 represent the attenuation of gamma rays by the tungsten layer for the various gamma sources in the core and layers between the core and the tungsten. The coefficient $\mu_{1,4}$ represents the attenuation by the tungsten of neutron dose due to neutrons born in the core. In contrast, $\mu_{5,3}$ represents the attenuation by lithium hydride in region 3 of neutrons which give rise to capture gamma sources in the tungsten (region 4).

Coefficients, such as $\mu_{5,4}$, describe the effect of the thickness of a source region (in this case tungsten) on the dose from its own source. Equation (2) becomes inadequate particularly when the thickness of this layer goes to zero. DOPEX does, however, set C_{im} equal to zero if a particular layer is eliminated by the code. At this point, however, the attenuation coefficients μ_{ijm} should be recalculated for the new configuration. Regions of origin of the various dose components are required data input to the code to facilitate this operation.

FITTING PARAMETERS TO DOSE-THICKNESS RELATION

The coefficients of equation (2) are obtained as precisely as possible by performing a series of transport calculations. A starting, base configuration is selected, preferably as close to an optimum configuration as possible. With the transport calculation, such as a discrete ordinates calculation, the individual dose components D_{im} are evaluated. Each layer of the base configuration to be altered by the optimization code is then systematically increased by a nominal amount (say, 1 cm) and the dose components are reevaluated with the transport code. From equation (2), then, for each m and i

$$D_{im}(t_{1m}, t_{2m}, \dots, t_{km}, \dots, t_{NREG\ m}) = C_{im} \exp \left(- \sum_{j=1}^{NREG} \mu_{ijm} t_{jm} \right)$$

$$D_{im}(t_{1m}, t_{2m}, \dots, t_{km} + \Delta t_{km}, \dots, t_{NREG\ m}) = C_{im} \exp \left(- \sum_{j=1}^{NREG} \mu_{ijm} t_{jm} \right) \cdot \exp(-\mu_{ikm} \Delta t_{km})$$

where $NREG$ is the number of layers in the problem. Solving the previous pair of equations for μ_{ikm} results in

$$\mu_{ikm} = \frac{1}{\Delta t_{km}} \ln \left[\frac{D_{im}(t_{1m}, t_{2m}, \dots, t_{km}, \dots, t_{NREG\ m})}{D_{im}(t_{1m}, t_{2m}, \dots, t_{km} + \Delta t_{km}, \dots, t_{NREG\ m})} \right]$$

The coefficients μ_{ijm} are determined for all i dose components, all j thicknesses, and all m directions in this manner.

The basic configuration data, that is, the set of thicknesses t_{jm} , dose components D_{im} , and "attenuation coefficients" μ_{ijm} , constitute the required input data. For the base configuration, then, the coefficient C_{im} is calculated by the code DOPEX from equation (2); that is,

$$C_{im} = D_{im} \exp \left(\sum_{j=1}^{NREG} \mu_{ijm} t_{jm} \right)$$

WEIGHT-MINIMIZATION PROCEDURE

The procedure for obtaining the minimum weight configuration by the method of steepest descent is presented in this section. The equations are from reference 6.

The mathematical problem to be solved is that of minimizing the weight w , a function of all thicknesses t_{jm} , while constraining the total doses D_m to some particular values; that is,

Minimize $w(t_{11}, t_{21}, t_{31}, \dots, t_{NREG\ 1}, t_{12}, t_{22}, \dots, t_{NREG\ 2}, \dots, t_{NREG\ M})$

with the following constraints:

$$(1) D_m = D_m^0 \quad \text{for } m = 1, 2, \dots, M$$

$$(2) t_{jm} \geq 0$$

$$(3) t_l = \text{constant for any desired values of } l$$

where M is the total number of constraints and D_m^0 is the value of the dose constraint in the m^{th} direction.

Constraint (2), non-negative shielding thickness, ensures a physically meaningful solution. The optional constraint (3), fixed thickness, is useful if it is desired that some thicknesses be kept from changing during the course of the calculation (e.g., the reactor core and reflector thicknesses). Constraint (3) is necessary for the spherical and cylindrical geometry programmed into DOPEX to prevent the trivial case of reducing the reactor core size to zero.

An n-dimensional Euclidean vector space with Cartesian coordinates $t_{11}, t_{21}, \dots, t_{\text{NREG } 1}, t_{12}, t_{22}, \dots, t_{\text{NREG } M}$ is defined. The following vectors are defined on this space:

$$\begin{aligned}\bar{t} &\equiv (t_{11}, t_{21}, \dots, t_{\text{NREG } 1}, t_{12}, t_{22}, \dots, t_{\text{NREG } 2}, \dots) \\ \bar{g} &\equiv \left(\frac{\partial w}{\partial t_{11}}, \frac{\partial w}{\partial t_{21}}, \dots, \frac{\partial w}{\partial t_{\text{NREG } 1}}, \frac{\partial w}{\partial t_{12}}, \frac{\partial w}{\partial t_{22}}, \dots, \frac{\partial w}{\partial t_{\text{NREG } M}} \right) \\ \bar{a}_m &\equiv \left(\frac{\partial D}{\partial t_{1m}}, \frac{\partial D}{\partial t_{2m}}, \dots, \frac{\partial D}{\partial t_{\text{NREG } m}} \right)\end{aligned}$$

The notation $\bar{t} = (t_{11}, t_{21}, \dots, t_{\text{NREG } M})$ means $t_1 \hat{X}_1 + t_2 \hat{X}_2 + \dots$ where \hat{X}_i are unit vectors in the i directions. Vectors \bar{g} and \bar{a} represent the gradient of weight and dose, respectively. The components of \bar{g} are evaluated from analytic expressions of weight as a function of thickness and depend on geometry. The components of \bar{a} are evaluated from the partial derivatives of (1) and (2), namely,

$$\begin{aligned}\frac{\partial D_m}{\partial t_{km}} &= \sum_{i=1}^{\text{IMAX}_m} \frac{\partial D_{im}}{\partial t_{km}} = \sum_{i=1}^{\text{IMAX}_m} \frac{\partial}{\partial t_{km}} C_{im} \left[\exp \left(- \sum_{j=1}^{\text{NREG}} \mu_{ijm} t_{jm} \right) \right] \\ &= \sum_{i=1}^{\text{IMAX}_m} (-\mu_{ikm}) C_{im} \exp \left(- \sum_{j=1}^{\text{NREG}} \mu_{ijm} t_{jm} \right) \\ &= - \sum_{i=1}^{\text{IMAX}_m} \mu_{ikm} D_{im}\end{aligned}$$

The unit vector \hat{u} (see ref. 6 for derivation)

$$\hat{u} = \frac{-\bar{g} + \frac{\bar{a}_1 \cdot \bar{g}}{\bar{a}_1 \cdot \bar{a}_1} \bar{a}_1 + \frac{\bar{a}_2 \cdot \bar{g}}{\bar{a}_2 \cdot \bar{a}_2} \bar{a}_2 + \dots + \frac{\bar{a}_M \cdot \bar{g}}{\bar{a}_M \cdot \bar{a}_M} \bar{a}_M}{\left[\bar{g} \cdot \bar{g} - \frac{(\bar{a}_1 \cdot \bar{g})^2}{\bar{a}_1 \cdot \bar{a}_1} - \frac{(\bar{a}_2 \cdot \bar{g})^2}{\bar{a}_2 \cdot \bar{a}_2} - \dots - \frac{(\bar{a}_M \cdot \bar{g})^2}{\bar{a}_M \cdot \bar{a}_M} \right]^{1/2}}$$

points in the direction of greatest weight decrease (steepest descent) along a hyperplane tangent to the hypersurface described by the equation

$$D_m(\bar{t}) = \text{constant} = D_m^0 \quad \text{for all } m = 1, 2, \dots, M$$

Components of \hat{u} represent increments of thickness to be added to each t_{jm} to approach the minimum weight criterion.

The optimization code proceeds as follows:

(1) A fraction f of \hat{u} is added to the thickness \bar{t} . The fraction f is an input parameter. (A value of $f = 1.0$ has given satisfactory results since $|\hat{u}| = 1$.)

(2) The new set of thicknesses generally does not return the correct dose constraint so a first-order correction is applied to each t to return to the dose constraint. That is requiring

$$D_m^0 = D_m(\bar{t} + \overline{dt}) = D_m(\bar{t}) + \nabla D_m(\bar{t}) \cdot \overline{dt}$$

one obtains (ref. 6)

$$\overline{dt} = \left[D_m^0 - D_m(\bar{t}) \right] \frac{\bar{a}_m}{\bar{a}_m \cdot \bar{a}_m}$$

Finally

$$\bar{t}_{\text{new}} = \bar{t} + \overline{dt}$$

Steps (1) and (2) are repeated until the relative change in weight from one iteration to the next is less than some prescribed value.

The code output includes final thicknesses and individual dose components as calculated from the dose-thickness relation for each iteration. It is incumbent on the user to make a final detailed proof calculation to verify the results of the prediction of the optimization code. Experiences have indicated that if input coefficients are determined accurately, final predictions of the optimization code are quite good provided the configuration is not radically changed. If the configuration is changed severely, a recalculation of coefficients is in order.

THE DOPEX CODE

In this section, the details of the DOPEX code are presented. Included here are:

- (1) General comments
- (2) A flow chart for data input
- (3) A sample problem and sample problem output

A complete FORTRAN IV listing appears in the appendix A.

The subroutines and their function in the DOPEX code are as follows:

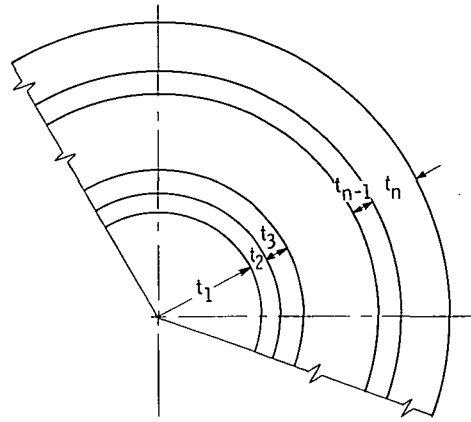
- (1) Main program - Calculates the steepest descent vector and alters shield thicknesses; calls subroutines INPUT, INIT, DOZE, WEIGHT, and CLEAR
- (2) Subroutine INPUT - Reads input data
- (3) Subroutine INIT - If input thicknesses do not result in the same dose rate as that required by the constraint, INIT is called to calculate a set of thicknesses which does meet the constraint so that the optimization procedure can begin. This calculation is carried out without regard to weight minimization. Calls subroutines DOZE, WEIGHT, and CLEAR.
- (4) Subroutine DOZE - Calculates dose rates and derivatives of dose with respect to thickness and products of dose and weight derivatives.
- (5) Subroutine WEIGHT - Calculates the total weight and derivatives of weight with respect to thickness.
- (6) Subroutine CLEAR - If a shield layer is eliminated in the course of the calculation, subroutine CLEAR is called to set that layer thickness to zero for the remainder of the calculation, set the constraint flag so that it is maintained at zero thickness, and zero out a dose component if it originated in the removed layer.

The DOPEX code as presented here includes the following geometry-dose-constraint situations:

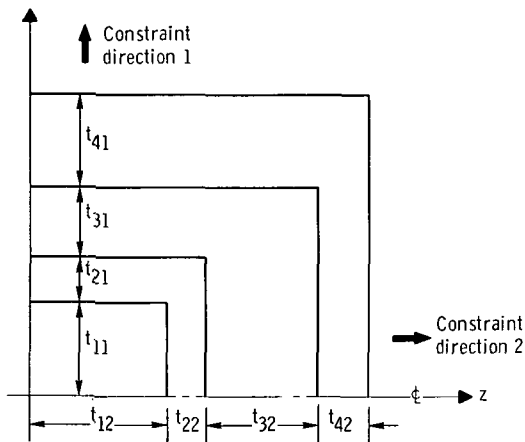
- (1) Spherical geometry, one dose constraint (this is the same as that presented in ref. 5)
- (2) Cylindrical geometry, two dose constraints
- (3) Cylindrical geometry, three dose constraints

These geometries are illustrated in figure 1. Different geometries will require a re-coding of subroutine weight to suit the application.

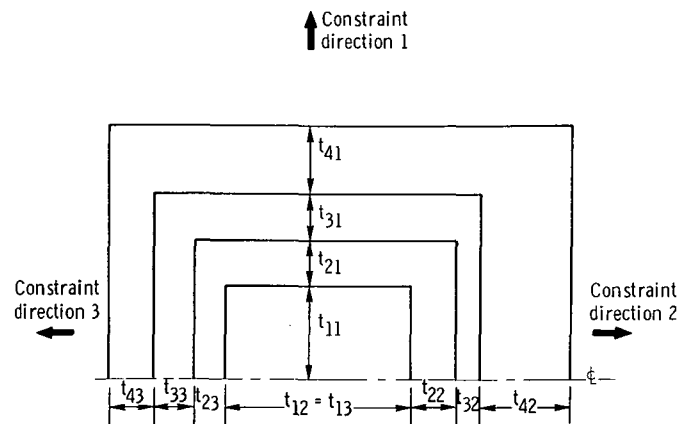
The cylindrical geometry (see fig. 1(b) and (c)) assumes the first dose constraint to be in the radial direction and the second and third to be on the $\pm z$ -axis as shown. Because of the way in which subroutine WEIGHT is coded, the number of layers in each direction must be the same as in the other directions. Furthermore, the density of the i^{th} layer in the first direction must be the same as that of the i^{th} layer in the second direction, and so on. If one has more shield layers in one direction than another, then one must artificially add layers such that there are the same number of contiguous regions in all directions. These added layers are fixed at zero thickness. Such a configuration is shown in figure 2. The present geometry will work with two or three



(a) One-constraint, spherical.



(b) Two-constraint, cylindrical (four regions illustrated in each direction).



(c) Three-constraint, cylindrical (four regions illustrated).

Figure 1. - DOPEX geometry.

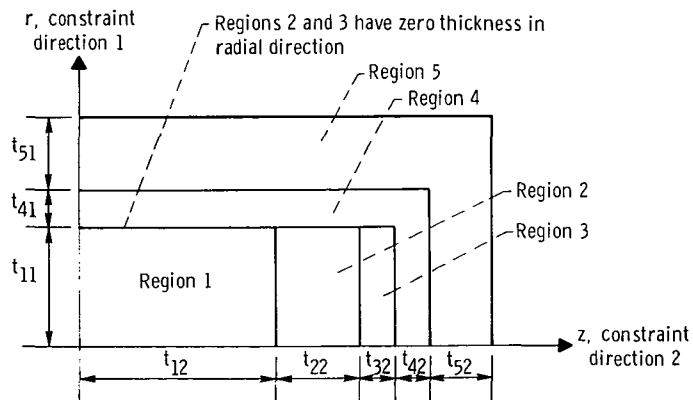



Figure 2. - Cylindrical geometry with two constraints, illustrating region designation to handle case of unequal number of shield layers in different directions.

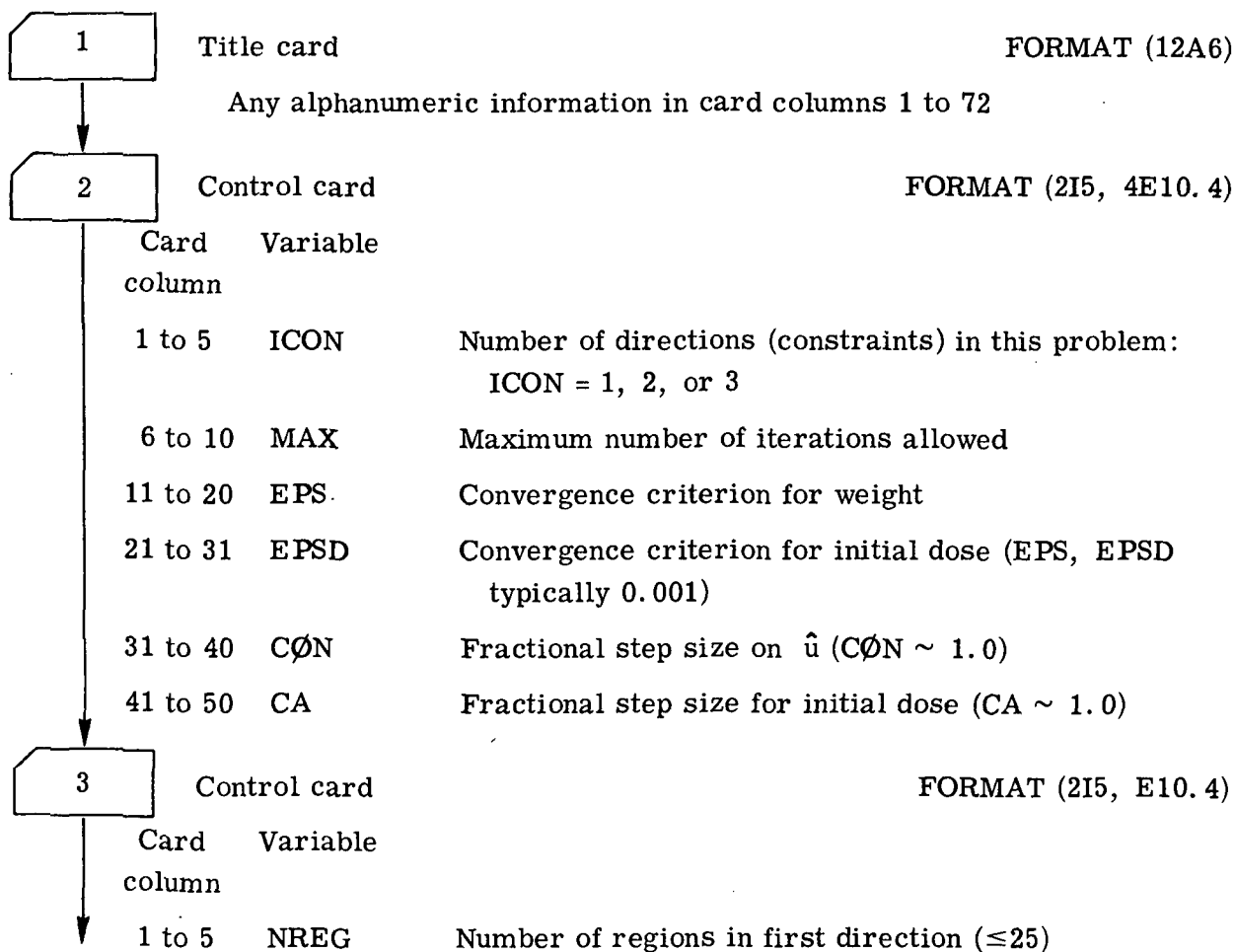
constraints. The required geometry data for input consists of a set of thicknesses for each region and direction. Radii are calculated internally. A thickness must be specified for each region.

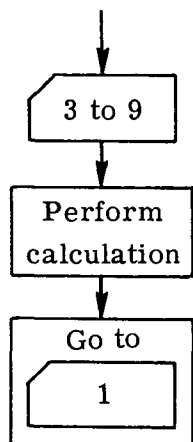
The code is constructed so that if one requires a new geometry, only a new subroutine WEIGHT is required. This subroutine calculates the system weight and all weight derivatives.

The code can presently handle up to 25 regions and dose components. Running times are typically less than 0.1 minute on the IBM 7094-II for a 12-region, 16 dose component problem.

Flow Chart for Data Input

The following is a flow chart for data input where the symbol  means read a card or set of cards as described:





Read cards 3 to 9 containing information pertaining to third direction.
(Required if ICON = 3.)

Sample Problem

A sample problem consisting of a reactor, molybdenum reflector, and a shield consisting of seven alternating layers of lithium hydride and tungsten is illustrated in figure 3. To illustrate the use of this code, the problem is run for the three constraint,

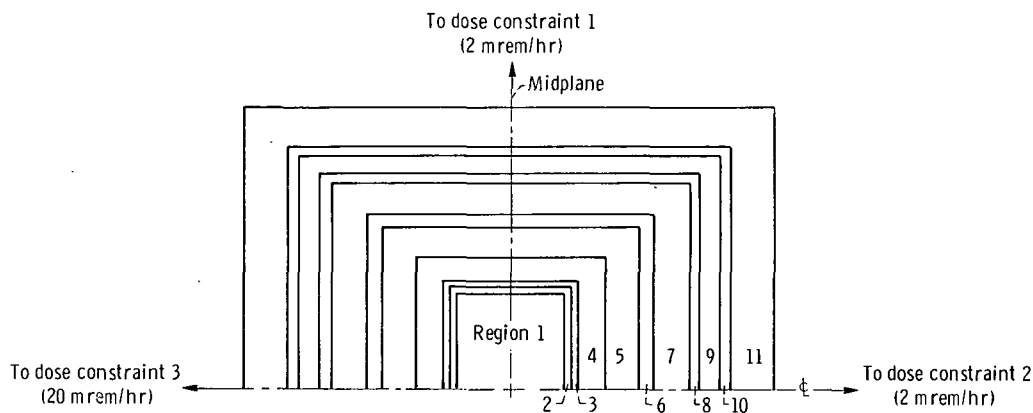


Figure 3. - Cylindrical geometry for sample problem.

cylindrical geometry. Region descriptions, densities, and initial thicknesses (guessed) are listed in table I. The configuration is to satisfy a dose constraint of 2 millirem per hour at a point 20 meters distant in the radial (first) direction, 2 millirem per hour 20 meters distant in the $+z$ (second) direction, and 20 millirem per hour 20 meters distant in the $-z$ (third) direction. A series of spherical discrete ordinates calculations for both neutrons and gamma rays were made to calculate doses from each source region for the initial set of thicknesses; perturbations were made to determine the attenuation coefficients μ_{ijm} . The results of these calculations are listed in tables II

TABLE I. - REGION DESCRIPTION

Region j	Description	Density, g/cm ³	Thickness, cm
1	Reactor core	9.957	26.0 (radius), 52.0 (height)
2	Plenum	8.647	2.50
3	Pressure vessel	16.763	.60
4	Molybdenum reflector	9.234	11.00
5	Lithium hydride	.75	^a 17.90
6	Tungsten	19.3	^a 7.00
7	Lithium hydride	.75	^a 14.00
8	Tungsten	19.3	^a 5.00
9	Lithium hydride	.75	^a 10.00
10	Tungsten	19.3	^a 3.50
11	Lithium hydride	.75	^a 59.50

^aInitial guess.TABLE II. - DOSE COMPONENTS CALCULATED
WITH INITIAL^a THICKNESSES

Dose component	Value of dose component, D _i , mrem/hr
1 Neutron	0.02430
2 Core gamma	.00303
3 Plenum, pressure vessel capture gamma	.00196
4 Plenum, pressure vessel inelastic gamma	.00220
5 Reflector capture gamma	.204
6 Reflector inelastic gamma	.00504
7 Region 6 tungsten capture gamma	.0921
8 Region 6 tungsten inelastic gamma	.00974
9 Region 8 tungsten capture gamma	.0988
10 Region 8 tungsten inelastic gamma	.0278
11 Region 10 tungsten capture gamma	.201
12 Region 10 tungsten inelastic gamma	.0947
Total	0.7647

^aFrom spherical calculations made with guessed shield thicknesses listed in table I. Assumed to apply in all directions of this cylindrical optimization calculation.

TABLE III. - COEFFICIENTS

Region j	Description	Dose component i											
		1	2	3	4	5	6	7	8	9	10	11	12
		Neutron	Core gamma	Plenum n, γ	Plenum n, n' γ	Reflector n, γ	Reflector n, n' γ	W(6) n, γ	W(6) n, n' γ	W(8) n, γ	W(8) n, n' γ	W(10) n, γ	W(10) n, n' γ
Coefficient, μ_{ij} , cm ⁻¹													
1	Core	0	0	0	0	0	0	0	0	0	0	0	0
2	Plenum	0	0	0	0	0	0	0	0	0	0	0	0
3	Pressure vessel	0	0	0	0	0	0	0	0	0	0	0	0
4	Reflector	0	0	0	0	0	0	0	0	0	0	0	0
5	Lithium hydride	.1347	.0189	.0147	.0147	.0212	.024	.3629	.2297	.2018	.1885	.1837	.1759
6	Tungsten	.2480	.774	.772	.772	.805	.795	.2719	.1812	.2386	.2536	.2543	.2577
7	Lithium hydride	.1369	.0228	.0204	.0204	.0167	.0206	.0210	.0250	.2257	.1983	.1910	.1795
8	Tungsten	.2316	.770	.766	.766	.790	.781	.798	.827	.1779	.1255	.2052	.2368
9	Lithium hydride	.1218	.024	.022	.022	.0201	.0239	.0187	.0245	.0230	.0250	.2231	.1808
10	Tungsten	.2306	.768	.763	.763	.805	.776	.782	.812	.810	.854	.2407	.1107
11	Lithium hydride	.1187	.0244	.0226	.0226	.0196	.0252	.0232	.0286	.0232	.0291	.0231	.0297

and III. Because the core radius, plenum, pressure vessel, and reflector thicknesses are to be constrained in this calculation, a value of μ_{ijm} equal 0.0 is assigned to these regions. The data calculated for the cylindrical case was determined from spherical discrete ordinates calculations and assumed to hold true for this cylindrical case; this may not, of course, be generally true.

The computer output for this sample problem is listed in appendix B. The output consists, first, of a listing of all input information, followed by the value of the dose constraint (DES), the value of the calculated dose for the initial configuration (DOS), and

TABLE IV. - FINAL SHIELD THICKNESS PREDICTIONS
FOR OPTIMIZED CYLINDRICAL SHIELD

Region	Description	Shield thickness, cm		
		Radial direction (2 mrem/hr)	+z direction (2 mrem/hr)	-z direction (20 mrem/hr)
5	Lithium hydride	20.37	17.19	14.72
6	Tungsten	9.48	7.65	6.11
7	Lithium hydride	9.76	13.12	9.97
8	Tungsten	2.20	4.14	3.72
9	Lithium hydride	11.28	9.32	6.26
10	Tungsten	3.24	2.80	2.09
11	Lithium hydride	41.35	54.39	53.73

the weight (WT) in grams of the initial configuration. If DES and DOS do not agree to within the parameter EPSD, a new set of thicknesses is calculated and printed out; this new set of thicknesses satisfies the dose constraint. The list of DES, DOS, and WT is followed by the values of the dose components $D(i)$ and the thicknesses of each region $T(i)$. For multidimensional calculations, the aforementioned blocks of data are repeated for each of the respective dose constraint directions as shown in figure 1. Following this, the results of each DOPEX iteration are listed. The data listed for each iteration are:

IT, the iteration count number

WT, the system weight (in units consistent with input data)

DOS, the calculated dose rates in each of the constraint directions

This is followed by the individual dose components $D(i)$ and the region thicknesses $T(i)$ for each of the respective constraint directions. The sample problem output shown in appendix B has been abbreviated to show the results of the first five and the last five

TABLE V. - DOSE COMPONENTS CALCULATED WITH OPTIMIZED THICKNESSES

Dose component	Value of dose component, D_i , mrem/hr		
	Radial direction	+z direction	-z direction
1 Neutron	0.2521	0.0735	0.4705
2 Core gamma	.0074	.0073	.0702
3 Plenum, pressure vessel capture gamma	.0046	.0046	.0430
4 Plenum, pressure vessel inelastic gamma	.0052	.0052	.0482
5 Reflector capture gamma	.4418	.4860	4.9452
6 Reflector inelastic gamma	.0120	.0122	.1234
7 Region 6 tungsten capture gamma	.3562	.3994	4.1715
8 Region 6 tungsten inelastic gamma	.0798	.0442	.3090
9 Region 8 tungsten capture gamma	.2601	.2801	2.8275
10 Region 8 tungsten inelastic gamma	.0629	.0767	.7146
11 Region 10 tungsten capture gamma	.3298	.4253	4.6897
12 Region 10 tungsten inelastic gamma	.1880	.1856	1.5871
Total	2.0	2.0	20.0

DOPEX iterations to avoid repetition. The final thicknesses and values of the dose components are listed in tables IV and V, respectively. The cylindrical problem here weighed 5.4×10^7 grams (119 000 lb) at the beginning of the optimization; the final weight was 4.33×10^7 grams (95 000 lb).

CONCLUDING REMARKS

A two-dimensional, two- or three-constraint radiation shield weight optimization code DOPEX has been developed. The code uses the steepest descent method to seek out a minimum. An empirical dose-thickness model is used by DOPEX; the user supplies appropriately fitted coefficients. The model assumes that doses in each principal direction are dependent upon thicknesses only in that direction. Such a model is valid for many cases of interest. Typical problems require about 0.1 minute of running time on an IBM 7094-II computer.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1972,
112-27.

APPENDIX A

FORTRAN IV LISTING

The IBM 7094-II FORTRAN IV listing for the DOPEX code is presented in this appendix. Subroutine WEIGHT is coded for the spherical and cylindrical geometries shown in figure 1.

\$IBFTC DOPEXC

```

C  ***D-OPEX ***** A ONE-, TWO-, OR THREE CONSTRAINT RADIATION
C  SHIELDING OPTIMIZATION CODE
C
C  THIS CODE IS BASED ON THE ONE-CONSTRAINT CODE,
C  OPEX-II, A STEEPEST-DESCENT-METHOD PROCEDURE.
C  THIS PROCEDURE WAS ORIGINALLY DEVELOPED FOR
C  ONE CONSTRAINT BY R.L.BERNICK OF ATOMICS INTL.
C
C  G.P.LAHTI  NASA-LEWIS RESEARCH CENTER
C
C  COMMON      ICON, MAX, EPS, EPSD, CON, CA, WT, GG, IT, IC,
1  DSTAR(3), NREG(3), T(25,3), RHO(25,3), NB(25,3),
2  IMAX(3), D(25,3), EMU(25,25,3), NIJ(25,3), DOSE(3), C(25,3),
3  A(25,3), AA(3), AG(3), U(25,3), G(25,3)
C
C  DIMENSION ALPHA(12)
7777 READ(5,500) ALPHA
    WRITE(6,600) ALPHA
    READ(5,505)  ICON,MAX,EPS,EPSD,CON,CA
    WRITE(6,605) ICON,MAX,EPS,EPSD,CON,CA
    DO 5 IC=1,ICON
      CALL INPUT(NREG(IC),IMAX(IC),DSTAR(IC), T(1,IC), RHO(1,IC),
1  NB(1,IC), EMU(1,1,IC), D(1,IC), NIJ(1,IC), C(1,IC))
5  CONTINUE
C
C  CALL WEIGHT
    WRITE(6,607) WT
C
C  FOR EACH OF THE IC DIRECTIONS, CALCULATE DOSE AND NORMALIZE TO
C  THE CONSTRAINT , IF NECESSARY
C  DO 10 IC=1,ICON
    CALL DOZE(NREG(IC), IMAX(IC), T(1,IC), EMU(1,1,IC), NB(1,IC),
1  C(1,IC), D(1,IC), A(1,IC), DOSE(IC), AA(IC), AG(IC), G(1,IC))
    IF(DSTAR(IC) .LE. C.0) GO TO 9
    CALL INIT(NREG(IC), IMAX(IC), T(1,IC), EMU(1,1,IC), NB(1,IC),
1  C(1,IC), D(1,IC), A(1,IC), DOSE(IC), AA(IC), AG(IC), G(1,IC),
2  DSTAR(IC))
    GO TO 10
9  DSTAR(IC)=DOSE(IC)
10 CONTINUE
C  UPDATE ALL DERIVATIVES
    CALL WEIGHT
    DO 15 IC=1,ICON
      CALL DOZE(NREG(IC), IMAX(IC), T(1,IC), EMU(1,1,IC), NB(1,IC),
1  C(1,IC), D(1,IC), A(1,IC), DOSE(IC), AA(IC), AG(IC), G(1,IC))

```

```

15 CONTINUE
C  **** THE ITERATION LOOP
    DO 100 IT =1, MAX
      W = WT
      DO 25 IC=1,ICON
        SQ=GG
        DO 20 IK=1,ICON
          20 SQ=SQ-AG(IK)**2/AA(IK)
          SQ=SQRT(SQ)
          NR=NREG(IC)
          DO 25 I =1, NR
            IF(NB(I,IC) .EQ. 0) GO TO 25
          C INCREMENT EACH THICKNESS
            V= AG(IC)*A(I,IC)/AA(IC) -G(I,IC)
            V=V/SQ
            U(I,IC)=V
            T(I,IC)=T(I,IC) + CON*V
            IF(T(I,IC) .LE. 0.0) CALL CLEAR(I,IMAX(IC))
          25 CONTINUE
            DO 30 IC=1,ICON
              NR=NREG(IC)
              CALL DOZE(NREG(IC), IMAX(IC), T(1,IC), EMU(1,1,IC), NB(1,IC),
                1 C(1,IC), D(1,IC), A(1,IC), DOSE(IC), AA(IC), AG(IC), G(1,IC))
          C RESTORE DOSE CONSTRAINT
            DO 30 I=1,NR
              IF(NB(I,IC) .EQ. 0) GO TO 30
              CONST=(DSTAR(IC)-DOSE(IC))/AA(IC)
              T(I,IC)=T(I,IC)+ CONST*A(I,IC)
              IF(T(I,IC) .LE. 0.0) CALL CLEAR(I,IMAX(IC))
            30 CONTINUE
          C UPDATE ALL DERIVATIVES
            CALL WEIGHT
            DO 35 IC=1,ICON
              CALL DOZE(NREG(IC), IMAX(IC), T(1,IC), EMU(1,1,IC), NB(1,IC),
                1 C(1,IC), D(1,IC), A(1,IC), DOSE(IC), AA(IC), AG(IC), G(1,IC))
            35 CONTINUE
          C WRITE OUT RESULTS OF THIS ITERATION
            WRITE(6,610) IT, WT, (DOSE(IC), IC=1,ICON)
            DO 45 IC=1,ICON
              IM=IMAX(IC)
              NR=NREG(IC)
              WRITE(6,615) (D(I,IC), I=1,IM)
            45 WRITE(6,620) (T(I,IC), I=1,NR)
              IF( ABS(WT-W)/ WT -EPS) 110, 110, 100
          100 CONTINUE
          110 GO TO 7777
          500 FORMAT(12A6)
          505 FORMAT(2I5, 4E10.4)
          600 FORMAT(1H1,12A6)
          605 FORMAT(9H0 ICON = I3/ 9H MAX = I3/
            1 / 9H EPS = 1PE12.4/ 9H EPSD = 1PE12.4/ 9H CON =
            2 1PE12.4/ 9H CA = 1PE12.4)
          607 FORMAT( 46H0 THE WEIGHT OF THE STARTING CONFIGURATION IS 1PE12.4)
          610 FORMAT(1H0/7H0 IT = I3,7X,5HWT = 1PE12.4,7X,
            X 7X,5HDOSE = 1P3E12.4)
          615 FORMAT( 7H0D(I)= 1P9E12.4/(7X,1P9E12.4))
          620 FORMAT(7H0T(I)= 1P9E12.4/(7X,1P9E12.4))
          END

```

\$IBFTC INPUT

```

SUBROUTINE INPUT (NREG,IMAX,DSTAR,T,RHO,NB,EMU,D,NIJ,C)
DIMENSION T(1), RHO(1), NB(1), EMU(25,25), D(1), NIJ(1), C(1)
COMMON      ICON, MAX, EPS, EPSD, CON, CA, WT, GG, IT, IC
READ(5,400) NREG, IMAX, DSTAR
WRITE(6,500) IC, NREG, IMAX, DSTAR
READ (5,401) (T(I), I=1,NREG)
READ (5,401) (RHO(I), I=1,NREG)
READ (5,403) (NB(I), I=1,NREG)
WRITE(6,510) ( I, T(I), RHO(I),NB(I), I = 1, NREG)
WRITE(6,550)
DO 7 J=1,NREG
READ (5,401) (EMU(I,J), I=1,IMAX)
7 WRITE (6,570) J,(EMU(I,J), I=1,IMAX)
READ (5,401) (D(I), I=1,IMAX)
READ(5,402) (NIJ(I), I=1,IMAX)
C NIJ(I) IS THE REGION NUMBER ASSOCIATED WITH THE ITH DOSE TERM
DOSE=0.0
DO 9 I=1,IMAX
DOSE=DOSE+D(I)
BB = 0.0
DO 8 J=1,NREG
8 BB = BB + EMU(I,J)*T(J)
9 C(I) = D(I)*EXP(BB)
WRITE(6,530) (I, C(I), D(I), NIJ(I), I=1,IMAX)
WRITE(6,540) DOSE
400 FORMAT(2I5, E10.4)
401 FORMAT(7E10.4)
402 FORMAT(14I5)
403 FORMAT(25I1)
500 FORMAT(9H0 IC = I3/ 9H NREG = I3/ 9H IMAX = I3/ 9H DSTAR =
1 1PE12.4)
510 FORMAT(1H0/34H0REGION T(I) RHO(I) NB(I)/(I7,2F10.3,I7))
530 FORMAT(1H0/34H0 I C(I) D(I) NIJ/(I5,1P2E12.4,I5))
540 FORMAT(17H0 TOTAL DOSE 1PE12.4)
550 FORMAT( 30H0REGION-J MU(I,J) )
570 FORMAT(I6, 3X, 1P9E12.4/(9X,1P9E12.4))
15 RETURN
END

```

\$IBFTC INITXX

```

SUBROUTINE INIT(NREG, IMAX, T, EMU, NB, C, D, A, DOS, AA, AG, G, DES)
DIMENSION T(1), EMU(25,25), NB(1), C(1), D(1), A(1), G(1), RHO(1)
COMMON      ICON, MAX, EPS, EPSD, CON, CA, WT, GG, IT, IC
Q= 1.0
DO 20 K =1,MAX
DOSA = DOS
AAA = SQRT(AA)
CONST = CA*Q /AAA
IF (DOS-DES) 10,25,5
5 CONST = -CONST
10 DO 15 I=1,NREG
IF( NB(I) .EQ. 0) GO TO 15
T(I) = T(I) + CONST * A(I)
IF( T(I).LE. 0.0) CALL CLEAR(I,IMAX)
15 CONTINUE
CALL DOZE(NREG, IMAX, T, EMU, NB, C, D, A, DOS , AA, AG, G)
IF( ABS(DOS-DES)/DES .LE. EPSD) GO TO 25
IF(((DOS-DES)*(DOSA-DES)) .LE. 0.0 ) Q = 0.5 * Q
20 CONTINUE
K = 777
25 CALL WEIGHT
WRITE(6, 30) K
WRITE(6, 35) (T(I), I=1,NREG )
WRITE(6, 40) DES, DOS, WT, (D(I), I=1,IMAX)
RETURN
30 FORMAT( 32H0INITIAL THICKNESSES FOUND AFTER I3,11H ITERATIONS)
35 FORMAT( 31H0CALCULATED INITIAL THICKNESSES/ (1P9E12.4))
40 FORMAT(7H0DES = 1PE12.4, 6X, 6HDOS = 1PE12.4, 6X, 5HWT = 1PE12.4/
1 7H0D(I)= 1P9E12.4/ (7X,1P9E12.4))
END

```

\$IBFTC CLEANX

```

SUBROUTINE CLEAR(J,IM)
COMMON      ICON, MAX, EPS, EPSD, CON, CA, WT, GG, IT, IC,
1 DSTAR(3), NREG(3), T(25,3), RHO(25,3), NB(25,3),
2 IMAX(3), D(25,3), EMU(25,25,3), NIJ(25,3), DOSE(3), C(25,3),
3 A(25,3), AA(3), AG(3), U(25,3), G(25,3)
C THE JTH REGION HAS JUST BEEN WIPED OUT IN THE ICTH DIRECTION
T(J,IC) = 0.0
NB(J,IC)= 0
DO 5 I=1,IM
IF(J .EQ. NIJ(I,IC)) C(I,IC)=0.0
5 CONTINUE
RETURN
END

```

\$IBFTC DOSEX

```

SUBROUTINE DOZE(NREG, IMAX, T, EMU, NB, C, D, A, DOS, AA, AG, G)
DIMENSION T(1), EMU(25,25), NB(1), C(1), D(1), A(1), G(1)
DOS = 0.0
DO 10 I=1,IMAX
  BB = 0.0
  DO 5 J=1,NREG
    5 BB = BB + EMU(I,J)* T(J)
  D(I) = C(I) * EXP(-BB)
10 DOS = DOS + D(I)
C   DOS IS TOTAL DOSE
C   A(K) = (D-DOSE)/(D-XK)
C   AA = A.A
C   AG = A.G
  AA = 0.0
  AG = 0.0
  DO 20 K = 1,NREG
    A(K) = 0.0
    IF( NB(K) .EQ. 0) GO TO 20
    DO 15 I = 1,IMAX
      15 A(K) = A(K) - EMU(I,K) * D(I)
      AA = AA + A(K)**2
      AG = AG + A(K)*G(K)
  20 CONTINUE
  RETURN
END

```

\$IBFTC CYLN3D

```

SUBROUTINE WEIGHT
COMMON ICON, MAX, EPS, EPSD, CON, CA, WT, GG, IT, IC,
1 DSTAR(3), NREG(3), T(25,3), RHO(25,3), NB(25,3),
2 IMAX(3), D(25,3), EMU(25,25,3), NIJ(25,3), DOSE(3), C(25,3),
3 A(25,3), AA(3), AG(3), U(25,3), G(25,3)
DIMENSION R(25), H(25)
GO TO (1,9,9),ICON
C   CODING FOR DOPEX SHIELDING OPTIMIZATION CODE
C   SPHERICAL SHELL GEOMETRY -G.P.LAHTI -NASA-LEWIS
C   FOR PLANE SLABS BOUNDED BY CONE OF HALF ANGLE THETA,
C   THIS SECTION MAY BE USED SIMPLY BY REPLACING
C   THE TERM FORPI BY PI*(TAN(THETA))**2
  DATA FORPI / 12.56636/
C   CALCULATE OUTER RADIUS OF EACH REGION, AND WEIGHT
  1 R(1)=T(1,1)
  RRR= R(1)**3
  WT = RHO(1,1)*RRR
  NR=NREG(1)
  DO 5 I=2,NR
    R3= RRR
    R(I)=R(I-1)+T(I,1)
    RRR= R(I)**3
    WT= WT + RHO(I,1)*(RRR-R3)
  5 CONTINUE
  WT=WT*FORPI/3.0

```



```

CALCULATE PARTIAL WT DERIVATIVES (DW/DX1) = G(I)
GG = G.G
GG=0.0
DO 7 I=1,NR
RR= 0.0
G(I,1)=0.0
IF(NB(I,1).EQ. 0) GO TO 7
DO 6 J=I,NR
R2= RR
RR= R(J)**2
6 G(I,1)=G(I,1)+RHO(J,1)*(RR-R2)
G(I,1)=G(I,1)*FORPI
GG = GG + G(I,1)**2
7 CONTINUE
RETURN
C CYLINDER SECTION
DATA PI / 3.14159/
9 NR=NREG(1)
R(1)=T(1,1)
H(1)=T(1,2)
IF( ICON.EQ.3) GO TO 11
DO 10 I=2,NR
R(I)=R(I-1)+T(I,1)
10 H(I)= H(I-1)+T(I,2)
GO TO 14
11 DO 12 I=2,NR
R(I)=R(I-1)+T(I,1)
12 H(I)= H(I-1)+T(I,2)+T(I,3)
C CALCULATE WEIGHT
14 RR=0.0
WT=0.0
DO 15 I=1,NR
RRR=RR
RR= R(I)**2 * H(I)
WT=WT+RHO(I,1)*(RR-RRR)
15 CONTINUE
WT=WT*PI
C CALCULATE PARTIAL DERIVATIVES IN THE RADIAL (FIRST) DIRECTION
C G(I,M)= D-W/D-T(I,M)
C GG=G.G
GG=0.0
DO 30 I=1,NR
G(I,1)=0.0
RR=0.0
IF(NB(I,1) .EQ. 0) GO TO 30
DO 25 J=I,NR
RRR=RR
RR=R(J)*H(J)
25 G(I,1)=G(I,1)+ RHO(J,1)*(RR-RRR)
G(I,1)=G(I,1)*2.0*PI
GG=GG+G(I,1)**2
30 CONTINUE
C CALCULATE PARTIAL DERIVATIVES IN THE AXIAL DIRECTION(S)
DO 45 M=2,ICON
DO 40 I=1,NR
G(I,M)=0.0
RR=0.0
IF(NB(I,M) .EQ. 0) GO TO 40

```

APPENDIX B

COMPUTER OUTPUT FROM SAMPLE PROBLEM

TEST CYLINDER GEOMETRY

ICON = 3
MAX = 50

EPS = 1.0000E-03
EPSD = 1.0000E-03
CON = 7.0000E-01
CA = 7.0000E-01

IC = 1
NREG = 11
IMAX = 12
DSTAR = 2.0000E+00

REGION	T(I)	RHO(I)	NB(I)
1	26.000	9.957	0
2	2.500	8.647	0
3	3.600	16.763	0
4	11.000	9.234	0
5	17.900	0.750	1
6	7.000	19.300	1
7	14.000	0.750	1
8	5.000	19.300	1
9	13.000	0.750	1
10	3.500	19.300	1
11	59.500	0.750	1

REGION-J	MU(I,J)									
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
2	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
5	1.3470E-01	1.8900E-02	1.4700E-02	1.4700E-02	2.1200E-02	2.4000E-02	3.6290E-01	2.2970E-01	2.0180E-01	
6	1.8850E-01	1.8370E-01	1.7590E-01	7.7200E-01	8.0500E-01	7.9500E-01	2.7190E-01	1.8120E-01	2.3860E-01	
7	2.4800E-01	7.7400E-01	7.7200E-01	2.5360E-01	2.5430E-01	2.5770E-01	2.0400E-02	1.6700E-02	2.0600E-02	
8	1.3690E-01	2.2800E-02	2.0400E-02	1.9830E-01	1.9100E-01	1.7950E-01	7.6600E-01	7.9000E-01	7.8100E-01	
9	2.3160E-01	7.7000E-01	7.6600E-01	1.2550E-01	2.0520E-01	2.3680E-01	7.9800E-01	8.2700E-01	1.7750E-01	
10	1.2180E-01	2.4000E-02	2.2000E-02	2.5000E-02	2.2310E-01	1.8080E-01	2.3900E-02	1.8700E-02	2.4500E-02	
11	2.3060E-01	7.6800E-01	7.6300E-01	8.5100E-01	2.4070E-01	1.1070E-01	7.8200E-01	8.1200E-01	8.1000E-01	
	1.1870E-01	2.4400E-02	2.2600E-02	2.9100E-02	2.3100E-02	2.9700E-02	2.3200E-02	2.8600E-02	2.3200E-02	

I	C(I)	D(I)	NIJ
1	2.9425E+05	2.4300E-02	1
2	4.9443E+03	3.0300E-03	1
3	2.3997E+03	1.9600E-03	2
4	2.6936E+03	2.2000E-03	3
5	3.5981E+05	2.0400E-01	4
6	1.1522E+04	5.0400E-03	4
7	2.1973E+06	9.2100E-02	6
8	2.2521E+04	9.7400E-03	6
9	9.5079E+04	9.8800E-02	8
10	2.0543E+04	2.7800E-02	8
11	1.1039E+05	2.0100E-01	10
12	2.8425E+04	9.4700E-02	10

TOTAL DOSE 7.6467E-01

IC = 2
NREG = 11
IMAX = 12
DSTAR = 2.0000E+00

REGION	T(I)	RHO(I)	NB(I)
1	52.000	9.957	0
2	2.500	8.647	0
3	0.600	16.763	0
4	11.000	9.234	0
5	17.900	0.750	1
6	7.000	19.300	1
7	14.000	0.750	1
8	5.000	19.300	1
9	10.000	0.750	1
10	3.500	19.300	1
11	59.500	0.750	1

REGION-J	MU(I,J)									
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
2	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
5	1.3470E-01	1.8900E-02	1.4700E-02	1.4700E-02	2.1200E-02	2.4000E-02	3.6290E-01	2.2970E-01	2.0180E-01	
6	1.8850E-01	1.8370E-01	1.7590E-01	7.7200E-01	8.0500E-01	7.9500E-01	2.7190E-01	1.8120E-01	2.3860E-01	
7	2.4800E-01	7.7400E-01	7.7200E-01	2.5770E-01	2.0400E-02	2.0400E-02	2.1000E-02	2.5000E-02	2.2570E-01	
8	2.5360E-01	2.5430E-01	2.0400E-02	1.7950E-01	7.6600E-01	7.9000E-01	7.8100E-01	7.9800E-01	8.2700E-01	1.7790E-01
9	1.9830E-01	1.9100E-01	2.3680E-01	2.2000E-02	2.0100E-02	2.3900E-02	1.8700E-02	2.4500E-02	2.3000E-02	
10	2.3160E-01	7.7000E-01	2.2000E-02	1.8080E-01	7.6300E-01	8.0500E-01	7.7600E-01	7.8200E-01	8.1200E-01	8.1000E-01
11	1.2550E-01	2.0520E-01	2.2600E-02	1.1070E-01	2.2600E-02	1.9600E-02	2.5200E-02	2.3200E-02	2.8600E-02	2.3200E-02

I	C(I)	D(I)	N(I)
1	2.9425E+05	2.4300E-02	1
2	4.9449E+03	3.0300E-03	1
3	2.3997E+03	1.9600E-03	2
4	2.6935E+03	2.2000E-03	3
5	3.5981E+05	2.0400E-01	4
6	1.1522E+04	5.0400E-03	4
7	2.1973E+06	9.2100E-02	6
8	2.2521E+04	9.7400E-03	6
9	9.5079E+04	9.8800E-02	8
10	2.0543E+04	2.7800E-02	8
11	1.1039E+05	2.0100E-01	10
12	2.8425E+04	9.4700E-02	10

TOTAL DOSE 7.6467E-01

IC = 3
NREG = 11
IMAX = 12
DSTAR = 2.3000E+01

REGION	T(I)	RHO(I)	NB(I)
1	52.000	9.957	0
2	2.500	8.647	0
3	0.600	16.763	0
4	11.000	9.234	0
5	17.900	0.750	1
6	7.000	19.300	1
7	14.000	0.750	1
8	5.000	19.300	1
9	10.000	0.750	1
10	3.500	19.300	1
11	59.500	0.750	1

REGION-J	MU(I,J)									
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
2	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
4	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.
5	1.3470E-01	1.8900E-02	1.4700E-02	1.4700E-02	2.1200E-02	2.4000E-02	3.6290E-01	2.2970E-01	2.0180E-01	
6	1.8850E-01	1.8370E-01	1.7590E-01	7.7200E-01	8.0500E-01	7.9500E-01	2.7190E-01	1.8120E-01	2.3860E-01	
7	2.4800E-01	7.7400E-01	7.7200E-01	2.5770E-01	2.0400E-02	2.0400E-02	2.1000E-02	2.5000E-02	2.2570E-01	
8	2.5360E-01	2.5430E-01	2.0400E-02	1.7950E-01	7.6600E-01	7.9000E-01	7.8100E-01	7.9800E-01	8.2700E-01	1.7790E-01
9	1.9830E-01	1.9100E-01	2.3680E-01	2.2000E-02	2.0100E-02	2.3900E-02	1.8700E-02	2.4500E-02	2.3000E-02	
10	2.3160E-01	7.7000E-01	2.2000E-02	1.8080E-01	7.6300E-01	8.0500E-01	7.7600E-01	7.8200E-01	8.1200E-01	8.1000E-01
11	1.2550E-01	2.0520E-01	2.2600E-02	1.1070E-01	2.2600E-02	1.9600E-02	2.5200E-02	2.3200E-02	2.8600E-02	2.3200E-02

8	2.3160E-01	7.7000E-01	7.6600E-01	7.6600E-01	7.9000E-01	7.8100E-01	7.9800E-01	8.2700E-01	1.7790E-01
	1.2550E-01	2.0520E-01	2.3680E-01						
9	1.2180E-01	2.4000E-02	2.2000E-02	2.2000E-02	2.0100E-02	2.3900E-02	1.8700E-02	2.4500E-02	2.3000E-02
	2.5000E-02	2.2310E-01	1.8080E-01						
10	2.3060E-01	7.6800E-01	7.6300E-01	7.6300E-01	8.0500E-01	7.7600E-01	7.8200E-01	8.1200E-01	8.1000E-01
	8.5100E-01	2.4070E-01	1.1070E-01						
11	1.1870E-01	2.4400E-02	2.2600E-02	2.2600E-02	1.9600E-02	2.5200E-02	2.3200E-02	2.8600E-02	2.3200E-02
	2.9100E-02	2.3100E-02	2.9700E-02						

I	C(I)	D(I)	NIJ
1	2.9425E+05	2.4300E-02	1
2	4.9449E+03	3.0300E-03	1
3	2.3997E+03	1.9600E-03	2
4	2.6935E+03	2.2000E-03	3
5	3.5981E+05	2.0400E-01	4
6	1.1522E+04	5.0400E-03	4
7	2.1973E+06	9.2100E-02	6
8	2.2521E+04	9.7400E-03	6
9	9.5079E+04	9.8800E-02	8
10	2.0543E+04	2.7800E-02	8
11	1.1033E+05	2.0100E-01	10
12	2.8425E+04	9.4700E-02	10

TOTAL DOSE 7.6467E-01

THE WEIGHT OF THE STARTING CONFIGURATION IS 5.3909E+07

INITIAL THICKNESSES FOUND AFTER 11 ITERATIONS

CALCULATED INITIAL THICKNESSES

2.6000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7701E+01 6.5022E+00 1.3850E+01 4.4536E+00 9.8800E+00
2.8226E+00 5.9468E+01

DES = 2.0000E+00 DOS = 2.0003E+00 WT = 5.0113E+07

D(I)= 3.8760E-02 1.1539E-02 7.4045E-03 8.3112E-03 8.1703E-01 1.9633E-02 2.9957E-01 3.0622E-02 2.2937E-01
6.4559E-02 3.2958E-01 1.4374E-01

INITIAL THICKNESSES FOUND AFTER 11 ITERATIONS

CALCULATED INITIAL THICKNESSES

5.2000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7701E+01 6.5022E+00 1.3850E+01 4.4536E+00 9.8800E+00
2.8226E+00 5.9468E+01

DES = 2.0000E+00 DOS = 2.0003E+00 WT = 4.9201E+07

D(I)= 3.8760E-02 1.1539E-02 7.4045E-03 8.3112E-03 8.1703E-01 1.9633E-02 2.9957E-01 3.0622E-02 2.2937E-01
6.4559E-02 3.2958E-01 1.4374E-01

INITIAL THICKNESSES FOUND AFTER 20 ITERATIONS

CALCULATED INITIAL THICKNESSES

5.2000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7467E+01 5.4819E+00 1.3721E+01 3.3008E+00 9.7869E+00
1.5166E+00 5.9425E+01

DES = 2.0000E+01 DOS = 2.0002E+01 WT = 4.6518E+07

D(I)= 9.4568E-02 1.7015E-01 1.0758E-01 1.2075E-01 1.3343E+01 3.0295E-01 3.0151E+00 2.9321E-01 1.1201E+00
3.1597E-01 8.1046E-01 3.0825E-01

IT = 1 WT = 4.6238E+07 DOS = 2.0001E+00 2.0000E+00 2.0000E+01

D(I)= 4.1448E-02 9.8925E-03 6.3319E-03 7.1073E-03 6.9410E-01 1.6738E-02 3.4004E-01 3.4888E-02 2.6515E-01
7.3822E-02 3.5850E-01 1.5208E-01

T(I)= 2.6000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7423E+01 6.8694E+00 1.3573E+01 4.4374E+00 9.7240E+00
2.6760E+00 5.9251E+01

D(I)= 3.9582E-02 1.1095E-02 7.1144E-03 7.9855E-03 7.8369E-01 1.8851E-02 3.1001E-01 3.1674E-02 2.3853E-01
6.5925E-02 3.3806E-01 1.4639E-01

T(I)= 5.2000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7621E+01 6.5937E+00 1.3772E+01 4.4498E+00 9.836CE+00
2.7926E+00 5.9413E+01

D(I)= 9.9193E-02 1.6426E-01 1.0370E-01 1.1640E-01 1.2850E+01 2.9202E-01 3.2723E+00 3.1576E-01 1.2439E+00
3.4959E-01 8.6825E-01 3.2424E-01

T(I)= 5.2000E+01 2.5000E+00 6.0000E-01 1.1000E+01 1.7301E+01 5.6021E+00 1.3567E+01 3.3193E+00 9.6856E+00
1.4368E+00 5.9361E+01

IT = 2 WT = 4.6016E+07 DOS = 2.0000E+00 2.0000E+00 2.0000E+01

D(I)= 4.3352E-02 8.5163E-03 5.4391E-03 6.1051E-03 5.9166E-01 1.4334E-02 3.7422E-01 3.8691E-02 2.5187E-01
8.0190E-02 3.8468E-01 1.6039E-01

T(I)=	2.5000E+01 2.6299E+00	2.5000E+00 5.8987E+01	6.0000E-01	1.1000E+01	1.7201E+01	7.2050E+00	1.3310E+01	4.3866E+00	9.5785E+00
D(I)=	4.0542E-02 6.9534E-02	1.0586E-02 3.4799E-01	6.7828E-03 1.4958E-01	7.6134E-03	7.4561E-01	1.7958E-02	3.2212E-01	3.2879E-02	2.4880E-01
T(I)=	5.2000E+01 2.7531E+00	2.5000E+00 5.9345E+01	6.0000E-01	1.1000E+01	1.7527E+01	6.6985E+00	1.3681E+01	4.4435E+00	9.7864E+00
D(I)=	1.0504E-01 3.9332E-01	1.5684E-01 9.4320E-01	9.8847E-02 3.4483E-01	1.1095E-01	1.2232E+01	2.7832E-01	3.5889E+00	3.4277E-01	1.4050E+00
T(I)=	5.2000E+01 1.3479E+00	2.5000E+00 5.9280E+01	6.0000E-01	1.1000E+01	1.7100E+01	5.7416E+00	1.3379E+01	3.3446E+00	9.5623E+00

IT =	3	WT =	4.5834E+07	DOS =	2.0000E+00	2.0000E+00	2.0000E+01		
D(I)=	4.6572E-02 8.2095E-02	7.5686E-03 4.0645E-01	4.8252E-03 1.6880E-01	5.4161E-03	5.2074E-01	1.2686E-02	3.9952E-01	4.1826E-02	3.0351E-01
T(I)=	2.6000E+01 2.6358E+00	2.5000E+00 5.8670E+01	6.0000E-01	1.1000E+01	1.7066E+01	7.4748E+00	1.3076E+01	4.2869E+00	9.4549E+00
D(I)=	4.1547E-02 7.2211E-02	1.0024E-02 3.5936E-01	6.4166E-03 1.5336E-01	7.2023E-03	7.0356E-01	1.6975E-02	3.3551E-01	3.4189E-02	2.5963E-01
T(I)=	5.2000E+01 2.7377E+00	2.5000E+00 5.9262E+01	6.0000E-01	1.1000E+01	1.7419E+01	6.8144E+00	1.3580E+01	4.4333E+00	9.7314E+00
D(I)=	1.1235E-01 4.4836E-01	1.4775E-01 1.0398E+00	9.2930E-02 3.7122E-01	1.0431E-01	1.1478E+01	2.6163E-01	3.9609E+00	3.7330E-01	1.6098E+00
T(I)=	5.2000E+01 1.2549E+00	2.5000E+00 5.9182E+01	6.0000E-01	1.1000E+01	1.6864E+01	5.8959E+00	1.3155E+01	3.3789E+00	9.4137E+00

IT =	4	WT =	4.5675E+07	DOS =	2.0000E+00	2.0000E+00	2.0000E+01		
D(I)=	4.9330E-02 8.0206E-02	7.0540E-03 4.2281E-01	4.4911E-03 1.7695E-01	5.0411E-03	4.8121E-01	1.1789E-02	4.1551E-01	4.4243E-02	3.0136E-01
T(I)=	2.6000E+01 2.6976E+00	2.5000E+00 5.8309E+01	6.0000E-01	1.1000E+01	1.7025E+01	7.6620E+00	1.2878E+01	4.1497E+00	9.3641E+00
D(I)=	4.2550E-02 7.4586E-02	9.4576E-03 3.7148E-01	6.0487E-03 1.5760E-01	6.7893E-03	6.6132E-01	1.5988E-02	3.4893E-01	3.5482E-02	2.6968E-01
T(I)=	5.2000E+01 2.7215E+00	2.5000E+00 5.9167E+01	6.0000E-01	1.1000E+01	1.7307E+01	6.9314E+00	1.3474E+01	4.4181E+00	9.6736E+00
D(I)=	1.2094E-01 5.1193E-01	1.3762E-01 1.1574E+00	8.6371E-02 4.0330E-01	9.6947E-02	1.0641E+01	2.4314E-01	4.3496E+00	4.0346E-01	1.6485E+00
T(I)=	5.2000E+01 1.1599E+00	2.5000E+00 5.9069E+01	6.0000E-01	1.1000E+01	1.6609E+01	6.0530E+00	1.2905E+01	3.4216E+00	9.2438E+00

IT =	5	WT =	4.5529E+07	DOS =	2.0000E+00	2.0000E+00	2.0000E+01		
D(I)=	5.2201E-02 7.6862E-02	6.8152E-03 4.3452E-01	4.3346E-03 1.8428E-01	4.8654E-03	4.6154E-01	1.1368E-02	4.2403E-01	4.6079E-02	2.9310E-01
T(I)=	2.6000E+01 2.7901E+00	2.5000E+00 5.7916E+01	6.0000E-01	1.1000E+01	1.7055E+01	7.7880E+00	1.2706E+01	4.0041E+00	9.3059E+00
D(I)=	4.3800E-02 7.6375E-02	8.9340E-03 3.8363E-01	5.7087E-03 1.6209E-01	6.4078E-03	6.2226E-01	1.5078E-02	3.6124E-01	3.6652E-02	2.7783E-01
T(I)=	5.2000E+01 2.7170E+00	2.5000E+00 5.9063E+01	6.0000E-01	1.1000E+01	1.7200E+01	7.0408E+00	1.3371E+01	4.3972E+00	9.6156E+00
D(I)=	1.3055E-01 5.7378E-01	1.2735E-01 1.2933E+00	7.9758E-02 4.4059E-01	8.9525E-02	9.7958E+00	2.2452E-01	4.7074E+00	4.2898E-01	2.1036E+00
T(I)=	5.2000E+01 1.1036E+00	2.5000E+00 5.8945E+01	6.0000E-01	1.1000E+01	1.6354E+01	6.1944E+00	1.2643E+01	3.4699E+00	9.0587E+00

IT =	29	WT =	4.3547E+07	DOS =	2.0000E+00	2.0000E+00	2.0000E+01		
D(I)=	1.9932E-01 6.1289E-02	7.2807E-03 3.7302E-01	4.5505E-03 2.0604E-01	5.1077E-03	4.4022E-01	1.1846E-02	3.6277E-01	7.1793E-02	2.5675E-01
T(I)=	2.6000E+01 3.3385E+00	2.5000E+00 4.4377E+01	6.0000E-01	1.1000E+01	1.9808E+01	9.1816E+00	9.8857E+00	2.3570E+00	1.0864E+01

D(I)=	6.8922E-02 7.2322E-02	7.0603E-03 4.4717E-01	4.4746E-03 1.9726E-01	5.0225E-03	4.7185E-01	1.1823E-02	3.9930E-01	4.3264E-02	2.7163E-01
T(I)=	5.2000E+01 2.9480E+00	2.5000E+00 5.5394E+01	6.0000E-01	1.1000E+01	1.7084E+01	7.6296E+00	1.2826E+01	4.0260E+00	9.2915E+00
D(I)=	4.3410E-01 6.8233E-01	6.8282E-02 4.8874E+00	4.1856E-02 1.6638E+00	4.6982E-02	4.8221E+00	1.2003E-01	4.1679E+00	3.0209E-01	2.7631E+00
T(I)=	5.2000E+01 2.2062E+00	2.5000E+00 5.4815E+01	6.0000E-01	1.1000E+01	1.4612E+01	6.0899E+00	9.7294E+00	3.6326E+00	6.2358E+00

IT = 30 WT = 4.3496E+07

DOS = 2.0000E+00 2.0000E+00 2.0000E+01

D(I)=	2.0945E-01 6.1571E-02	7.3122E-03 3.6473E-01	4.5672E-03 2.0291E-01	5.1265E-03	4.4050E-01	1.1887E-02	3.6121E-01	7.3260E-02	2.5748E-01
T(I)=	2.6000E+01 3.3240E+00	2.5000E+00 4.3763E+01	6.0000E-01	1.1000E+01	1.9920E+01	9.2394E+00	9.8451E+00	2.3228E+00	1.0952E+01
D(I)=	6.9740E-02 7.3094E-02	7.1016E-03 4.4326E-01	4.5000E-03 1.9521E-01	5.0510E-03	4.7452E-01	1.1893E-02	3.9897E-01	4.3419E-02	2.7324E-01
T(I)=	5.2000E+01 2.9223E+00	2.5000E+00 5.5201E+01	6.0000E-01	1.1000E+01	1.7107E+01	7.6327E+00	1.2872E+01	4.0449E+00	9.2990E+00
D(I)=	4.4145E-01 6.8588E-01	6.8613E-02 4.8585E+00	4.2050E-02 1.6534E+00	4.7199E-02	4.8429E+00	1.2062E-01	4.1640E+00	3.0307E-01	2.7714E+00
T(I)=	5.2000E+01 2.1700E+00	2.5000E+00 5.4608E+01	6.0000E-01	1.1000E+01	1.4633E+01	6.0932E+00	9.7640E+00	3.6441E+00	6.2404E+00

IT = 31 WT = 4.3448E+07

DOS = 2.0000E+00 2.0000E+00 2.0000E+01

D(I)=	2.1983E-01 6.1873E-02	7.3434E-03 3.5623E-01	4.5838E-03 1.9953E-01	5.1451E-03	4.4079E-01	1.1927E-02	3.5977E-01	7.4793E-02	2.5819E-01
T(I)=	2.6000E+01 3.3067E+00	2.5000E+00 4.3151E+01	6.0000E-01	1.1000E+01	2.0032E+01	9.2983E+00	9.8120E+00	2.2903E+00	1.1038E+01
D(I)=	7.0563E-02 7.3918E-02	7.1437E-03 4.3911E-01	4.5259E-03 1.9301E-01	5.0801E-03	4.7727E-01	1.1964E-02	3.9881E-01	4.3588E-02	2.7492E-01
T(I)=	5.2000E+01 2.8945E+00	2.5000E+00 5.5005E+01	6.0000E-01	1.1000E+01	1.7130E+01	7.6359E+00	1.2925E+01	4.0657E+00	9.2056E+00
D(I)=	4.4370E-01 6.9254E-01	6.8970E-02 4.8233E+00	4.2260E-02 1.6401E+00	4.7434E-02	4.8659E+00	1.2126E-01	4.1627E+00	3.0429E-01	2.7826E+00
T(I)=	5.2000E+01 2.1598E+00	2.5000E+00 5.4396E+01	6.0000E-01	1.1000E+01	1.4654E+01	6.0972E+00	9.8055E+00	3.6583E+00	6.2461E+00

IT = 32 WT = 4.3401E+07

DOS = 2.0000E+00 2.0000E+00 2.0000E+01

D(I)=	2.3041E-01 6.2193E-02	7.3742E-03 3.4756E-01	4.6002E-03 1.9591E-01	5.1635E-03	4.4110E-01	1.1967E-02	3.5845E-01	7.6397E-02	2.5888E-01
T(I)=	2.6000E+01 3.2865E+00	2.5000E+00 4.2545E+01	6.0000E-01	1.1000E+01	2.0145E+01	9.3584E+00	9.7863E+00	2.2591E+00	1.1123E+01
D(I)=	7.1592E-02 7.4788E-02	7.1865E-03 4.3473E-01	4.5523E-03 1.9066E-01	5.1097E-03	4.8010E-01	1.2037E-02	3.9882E-01	4.3771E-02	2.7665E-01
T(I)=	5.2000E+01 2.8547E+00	2.5000E+00 5.4804E+01	6.0000E-01	1.1000E+01	1.7151E+01	7.6392E+00	1.2984E+01	4.0883E+00	9.2110E+00
D(I)=	4.5591E-01 6.9914E-01	6.9349E-02 4.7829E+00	4.2483E-02 1.6244E+00	4.7685E-02	4.8908E+00	1.2193E-01	4.1636E+00	3.0570E-01	2.7961E+00
T(I)=	5.2000E+01 2.1461E+00	2.5000E+00 5.4180E+01	6.0000E-01	1.1000E+01	1.4675E+01	6.1018E+00	9.8540E+00	3.6749E+00	6.2522E+00

IT = 33 WT = 4.3357E+07

DOS = 2.0000E+00 2.0000E+00 2.0000E+01

D(I)=	2.4118E-01 6.2528E-02	7.4048E-03 3.3874E-01	4.6165E-03 1.9206E-01	5.1818E-03	4.4143E-01	1.2005E-02	3.5725E-01	7.8078E-02	2.5953E-01
T(I)=	2.6000E+01 3.2636E+00	2.5000E+00 4.1943E+01	6.0000E-01	1.1000E+01	2.0259E+01	9.4198E+00	9.7679E+00	2.2292E+00	1.1204E+01
D(I)=	7.2532E-02 7.5700E-02	7.2300E-03 4.3014E-01	4.5790E-03 1.8818E-01	5.1397E-03	4.8299E-01	1.2112E-02	3.9902E-01	4.3971E-02	2.7841E-01

T(I)=	5.2330E+01 2.8330E+00	2.5000E+00 5.4599E+01	6.0000E-01	1.1000E+01	1.7171E+01	7.6426E+00	1.3050E+01	4.1126E+00	9.2149E+00
D(I)=	4.6315E-01 7.0554E-01	6.9745E-02 4.7382E+00	4.2716E-02 1.6066E+00	4.7947E-02	4.9173E+00	1.2264E-01	4.1665E+00	3.0729E-01	2.8112E+00
T(I)=	5.2330E+01 2.1192E+00	2.5000E+00 5.3957E+01	6.0000E-01	1.1000E+01	1.4696E+01	6.1069E+00	9.9095E+00	3.6939E+00	6.2582E+00

IT =	34	WT =	4.3314E+07	DOS =	2.0000E+00	2.0000E+00	2.0000E+01		
D(I)=	2.5237E-01 6.2876E-02	7.4352E-03 3.2980E-01	4.6328E-03 1.8800E-01	5.2001E-03	4.4178E-01	1.2043E-02	3.5616E-01	7.9845E-02	2.6014E-01
T(I)=	2.6330E+01 3.2378E+00	2.5000E+00 4.1347E+01	6.0000E-01	1.1000E+01	2.0374E+01	9.4826E+00	9.7567E+00	2.2004E+00	1.1284E+01
D(I)=	7.3484E-02 7.6550E-02	7.2743E-03 4.2534E-01	4.6062E-03 1.8557E-01	5.1703E-03	4.8595E-01	1.2188E-02	3.9942E-01	4.4187E-02	2.6016E-01
T(I)=	5.2330E+01 2.7993E+00	2.5000E+00 5.4388E+01	6.0000E-01	1.1000E+01	1.7190E+01	7.6461E+00	1.3123E+01	4.1387E+00	9.3172E+00
D(I)=	4.7345E-01 7.1461E-01	7.0157E-02 4.6897E+00	4.2959E-02 1.5871E+00	4.8220E-02	4.9452E+00	1.2338E-01	4.1715E+00	3.0904E-01	2.6275E+00
T(I)=	5.2330E+01 2.0895E+00	2.5000E+00 5.3729E+01	6.0000E-01	1.1000E+01	1.4717E+01	6.1124E+00	9.9723E+00	3.7150E+00	6.2634E+00

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